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PROBABILISTIC DEMAND MODEL AND FRAGILITY ESTIMATES FOR CRITICAL FAILURE MODE OF UN-ANCHORE STEEL STORAGE TANKS

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ABSTRACT

Large-capacity un-anchored on-grade cylindrical tanks are used to store variety products of petroleum, chemicals, and liquefied natural gas in petroleum complexes. Tanks that were inadequately designed or detailed have suffered extensive damages during past earthquakes. The main objective of this paper is to develop probabilistic demand models for Elephant Foot Buckling (EFB) and welding failure at the connection between bottom plate and shell based on FEM analytical data and use the Bayesian statistical technique to assess the specific critical failure mode fragility of un-anchored on-grade steel storage tanks with 90% fill percentage. Developed probabilistic demand models are used to compare the fragility of critical failure modes of selected tanks and real world data. The approach can be applied for other failure modes and other equipments, as well.

Introduction

The seismic vulnerability is often characterized by fragility curves which are the conditional probability of different levels of component damage as a function of some measure of the seismic hazard. Existing fragilities are mostly based on empirical models relied on statistical data which can be gathered from post earthquake field studies. These data are often characterized by incomplete information, measurement errors and qualitative, indirect nature of observation (Berahman and Behnamfar 2007 and 2009). The main objective of this paper is to use the Bayesian statistical technique to assess the specific critical failure mode fragility of un-anchored on-grade steel storage tanks with 90% fill percentage based on Finite Elements analytical data. This level of filling has been selected because past earthquakes have shown that tanks with higher levels of filling are more vulnerable during earthquake (O,Rourke and So 2000). The Bayesian technique can properly account for all prevailing uncertainties (Der Kiureghian 2002). Furthermore, the Bayesian approach can incorporate, in a rational and systematic manner, information gained from subjective engineering judgment that is often essential in the assessment of lifeline vulnerability and fragility. Details of the Bayesian technique can be found in the existing literature e.g. (Box and Tiao 1992), (Der Kiureghian 1999), and (Der Kiureghian 2002).

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Analytical Data

The finite elements method may be used independently to solve the fluid-structure problems. In this paper, both liquid and structure have been modelled directly with finite elements, displacement variables have been used as degrees of freedom for liquid and for structure, and Gap elements have been used to allow for base plate uplift. To perform the required numerical analysis, the general purpose nonlinear finite element program ANSYS is used. Fig.1 shows the three dimensional model of tank with fluid inside.

For the purpose of this work, 16 tanks were selected for further study. The tanks range in H/R(ratio of product level to nominal tank radius) from 0.54 to 1.92 and in ts/tb (ratio of shell plate thickness to bottom plate thickness) from 1 to 4.85. For nonlinear time-history analysis, 12 records were selected. The peak ground acceleration ranges from 75 cm/s^2 to 1038 cm/s^2, peak ground velocity ranges from 3.38cm/s to 66 cm/s, peak ground displacement ranges from 0.52 cm to 37.34cm, and also duration of strong ground motion ranges from 2.86s to 37.08s. In the selection of these ground motions, effort has been made to select the records which have been recorded on very firm to rock ground conditions.

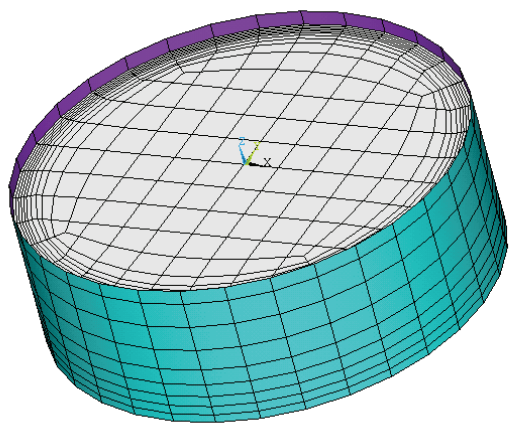

Figure 1. Three dimensional model of tank with fluid inside.

Probabilistic Demand Model

In the context of this work, a "demand model" is a mathematical expression relating the demand on a structural component of the tank due to earthquake, to a set of measurable variables $\mathbf{x} = (\mathbf{x_1}, \mathbf{x_2}, ...)$, e.g., material property constants, member dimensions, or imposed boundary conditions. The main purpose of the model is to provide a means for predicting the quantities of interest for given deterministic or random values of the variables $\mathbf{x}$. Eq. 1 shows the general form of uni-variate demand model.

$$D = D(\mathbf{x}, \Theta), \tag{1}$$

where Θ denotes a set of parameters introduced into the model to "fit" the model to the observed data and D is the demand quantity of interest. The function $D(\mathbf{x},\Theta)$ can have a general form involving algebraic expressions, integrals, or derivatives. Ideally, it should be derived from basic principles, e.g., the rules of mechanics. For the applications in this paper, a deterministic model, to which some correction terms is added, was adopted as the demand model which is presented in Eq. 2,

$$D(\mathbf{x},\Theta) = \hat{D}(\mathbf{x}) + \gamma(\mathbf{x},\boldsymbol{\theta}) + \sigma\varepsilon, \tag{2}$$

where $\hat{D}(\mathbf{x})$ is a selected deterministic model, $\gamma(\mathbf{x},\boldsymbol{\theta})$ is a correction term for the bias inherent in the deterministic model that is expressed as a function of the variables $\mathbf{x}$ and parameters $\boldsymbol{\theta} = (\theta_1, \theta_2, \ldots)$, ε is a normal random variable with zero mean and unit variance, σ represents the standard deviation of the model error, and $\Theta = (\boldsymbol{\theta}, \sigma)$ denotes the set of unknown model parameters. Note that for given $\mathbf{x}$, $\boldsymbol{\theta}$, and σ, the variance of the model will be:

$$Var[D(\mathbf{x},\Theta)] = \sigma^2 \tag{3}$$

The function $\gamma(\mathbf{x},\boldsymbol{\theta})$ corrects the bias in the deterministic model $\hat{D}(\mathbf{x})$. Since the deterministic model usually involves approximations, the true form of $\gamma(\mathbf{x},\boldsymbol{\theta})$ is unknown. In order to explore the sources of bias in the deterministic model, a suitable set of p "explanatory" basis functions $h_i(\mathbf{x}), i = 1, \ldots, p$ can be selected to express the bias correction term as follows:

$$\gamma(\mathbf{x},\boldsymbol{\theta}) = \sum_{i=1}^{p} \theta_i h_i(\mathbf{x}) \tag{4}$$

By examining the posterior statistics of the unknown parameters θ_i, one is able to identify those explanatory functions that are significant in describing the bias in the deterministic model. Note that while the bias correction term is linear in the parameters θ_i, it is not necessarily linear in the basic variables $\mathbf{x}$.

Probabilistic Elephant Foot Buckling Demand Model

The failure mode EFB exhibits one or several permanent buckling near the base of the tank. These may extend around part or entire of shell circumference. Experimental studies of liquid storage tanks under dynamic excitation were done by Jia and Ketter (Jia and Ketter 1989), their results showed that the EFB represents a combined inelastic strength and stability problem. The interaction between the axial compression and the circumferential hoop tension should be considered when evaluating the allowable axial compressive stress. This is because at the critical sections, where buckling occurs, the shell is subjected to significant bi-axial stresses. The magnitude of hoop tension may be of a non-negligible order, even when considering hydrostatic loading alone. Once hydrodynamic loading due to seismic excitation is imposed, this hoop tension increases considerably at the exact location where the axial compression is greatest. The stress resultant thus obtained tends to reach Tresca's yielding condition and inelastic instability results as the tests by Jia and Ketter has revealed. Therefore EFB is most related to this combined stress effect.

Base on the above description, the deterministic demand model for EFB has been considered as following:

$$\hat{T}(\mathbf{x}) = \frac{\hat{\sigma}_x - \hat{\sigma}_y}{2} \tag{5}$$

In which $\hat{\sigma}_y$ (MPa) is the axial compression stress due to earthquake overturning and $\hat{\sigma}_x$ (MPa) is the hoop tension stress given in API (API 2005). Thus the probabilistic model can be represented as in Eq.6.

$$Ln\left[T(\mathbf{x},\Theta)\right] = Ln\left[\hat{T}(\mathbf{x})\right] + \gamma_T(\mathbf{x},\boldsymbol{\theta}) + \sigma_T\varepsilon \tag{6}$$

where $\Theta = (\mathbf{x},\boldsymbol{\theta})$ is the set of unknown model parameters, $\gamma_T(\mathbf{x},\boldsymbol{\theta})$ is a correction term for the bias inherent in the deterministic model, and ε is a standard normal random variable (i.e., with zero mean and unit variance). $\sigma_T\varepsilon$. represents the random component of the model error. Thus, σ denotes the standard deviation of the model error and is a measure of the quality of the model. Because of the employed logarithmic transformation, one can show that σ is approximately equal to the coefficient of variation of the Tresca yielding ratio. $\gamma_T(\mathbf{x},\boldsymbol{\theta})$ will be defined in the following section.

Model Correction

The term $\gamma_T(\mathbf{x},\boldsymbol{\theta})$ on the right-hand side of Eq. 6, is intended to correct the bias inherent in the deterministic model $Ln\left[\hat{T}(\mathbf{x})\right]$. This is shown as below:

$$\gamma_T(\mathbf{x},\boldsymbol{\theta}) = \sum_{i=1}^{p} \theta_i h_i(\mathbf{x}) \tag{7}$$

where $\boldsymbol{\theta} = (\theta_1, \theta_2, ...)$ is a vector of unknown model parameters and $h_1(\mathbf{x}),...,h_p(\mathbf{x})$ are selected "explanatory" functions. To capture a potential bias in the model that is independent of the variable $\mathbf{x}$, $h_1(\mathbf{x})$ is selected to be 1. To detect any possible under- or over-estimation of the individual contributions defined in the deterministic model (Eq. 5) to the total value , $h_2(\mathbf{x})$ is selected to be $Ln((\hat{\sigma}_x - \hat{\sigma}_y)/240)$. To capture the effect of physical configuration of tank, $h_4(\mathbf{x}) = H/R$ (ratio of product level to nominal tank radius), $h_5(\mathbf{x}) = t_b/R$ (ratio of thickness of tank bottom plate to nominal tank radius), $h_6(\mathbf{x}) = t_s/R$ (ratio of thickness of tank shell plate to nominal tank radius) are selected. Also in order to incorporate the effects of seismic overturning moments, $h_3(\mathbf{x})$ is selected to be $M/(D^2(w_a + w_t))$ in which, w_a is the resisting force of tank per unit length of shell circumference (N/m), w_t is the tank and roof weight acting at the base of the shell (N/m), D is nominal diameter of tank. To detect the effect of earthquake on structure, $h_8(x) = Sa_i$ dimensionless spectral acceleration at the first impulsive mode of tank, $h_9(x) = Sa_c$ dimensionless spectral acceleration at the first convective mode of tank are selected. To explore the effect of soil, the ratio of tank stiffness to soil stiffness as $h_7(\mathbf{x}) = kt_b/P$ is introduced, where k=1e8 N/m (soil stiffness for stiff soil) and P is the liquid pressure on bottom plate, $P = \rho g H$, where ρ is the density of the liquid N/m^3, and H is the product level.

Parameter Estimation

For each tank and each earthquake, the deterministic demand was calculated based on Eq. 5. Nonlinear time history analysis was conducted and maximum axial and tension stresses at shell bottom course were calculated. The probabilistic model in Eq. 6 was assessed by estimation of its parameter $\Theta = (\theta_1, ..., \theta_9, \sigma_T)$ using Bayesian updating formula. Analysis revealed that $h_1(x), h_5(x)$, and $h_9(x)$ do not have a strong contribution for predicting EFB demand level. Table 1 lists the posterior statistics of the remaining parameters, and Fig.2 represent the comparison between the predicted demand by the probabilistic model (Eq. 6) and the measured values based on nonlinear analysis results.

Table 1. Posterior statistics of the parameters in the EFB demand model

			Correlation coefficient						
Parameter	Mean	St- dev	σ	θ_2	θ_3	θ_4	θ_6	θ_7	θ_8
σ	0.19	0.00209	1						
θ_2	-0.47	0.0465	0.0058	1					
θ_3	-0.05	0.0196	-0.014	-0.137	1				
θ_4	0.147	0.0369	0.0073	-0.0039	-0.247	1			
θ_6	-159.6	36.2	0.0056	0.566	0.163	-0.51	1		
θ_7	0.00668	0.0047	8.28e-4	0.44	-0.064	-0.369	0.01219	1	
θ_8	0.1037	0.024	0.00568	-0.29	-0.76	0.134	-0.466	-0.098	1

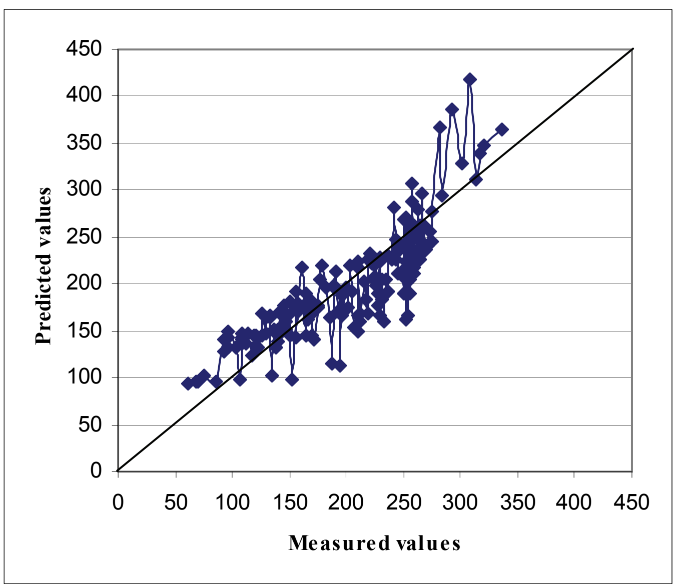

Figure. 2. Comparison between the measured and the predicted EFB demand values.

Probabilistic Demand Model for Welding Failure at the Connection Between Shell and Bottom Plate.

One of the critical failure modes in un-anchored on-grade steel storage tanks is rupture at the bottom plate and shell junction. This rupture happens due to base uplifting during earthquake and accordingly excessive joint stresses. This mode of failure may cause leakage and extensive fire in an industrial plant. In this section, the deterministic and probabilistic models for this failure mode are presented. From Fig. 3 the required plastic rotation for an uplift of v and a base separation of L_b, is

$$\theta_p = \left(\frac{2v}{L_b} - \frac{v}{2R}\right) \leq 0.2. \tag{8}$$

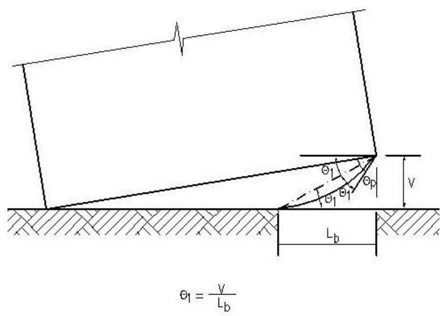

Figure.3. Plastic rotation of base plate of uplifting tank

Based on the tank behavior in the past earthquakes as well as the analytical data, the dimensionless probabilistic demand model for welding failure at the connection between shell and bottom plate is proposed as Eq. 9

$$\theta_P(\mathbf{x}\ ,\ \mathbf{\Theta}) = \gamma_{\theta_p}(\mathbf{x},\ \mathbf{\eta}) + \sigma_{\theta_p}\varepsilon \tag{9}$$

where $\mathbf{\Theta} = (\mathbf{\eta}\ ,\ \sigma_{\theta_p})$ is the set of unknown model parameters, $\gamma_{\theta_p}(\mathbf{X},\mathbf{\eta})$, as shown in Eq. 10, is the predictive model and ε is a standard normal random variable with zero mean and σ_{θ_p} is the standard deviation.

$$\gamma_{\theta_p}(\mathbf{x}\ ,\ \mathbf{\eta}) = \eta_1 \frac{M}{D^2(w_a + w_t)} + \eta_2 \frac{H}{R} + \eta_3 \frac{t_b}{R} + \eta_4 \frac{kt_b}{P} + \eta_5 Sai \tag{10}$$

Bayesian updating rule was used to calculate the posterior statistics of model parameters. Table 2 lists the posterior statistics of the parameters.

Assessment of Seismic Fragility

In structural reliability, the failure event for a component is usually described in terms of a limit-state function that defines the boundary between the failure and safe domains of performance. Let $g(\mathbf{x},\mathbf{\Theta})$ define this function for a given component, where $\mathbf{x}$ denotes the set of random variables (with aleatory uncertainties) affecting the state of the component and $\mathbf{\Theta}$ denotes the set of model parameters. By convention, this function is formulated in such a way that $g(\mathbf{x},\mathbf{\Theta}) \leq 0$ denotes the failure event. With the above definitions, the limit-state function for each failure mode is defined as presented in Eq. 11, in which C is the tank capacity for a particular failure mode, and D is the seismic demand:

$$g(\mathbf{x},\ \varepsilon;\ \mathbf{\Theta};\ Sa_i) = C - D, \tag{11}$$

Table 2. Posterior statistics of the parameters for the demand model of the welding failure at the connection between shell and bottom plate.

			Correlation coefficient					
Parameter	Mean	Stdev	σ	η_1	η_2	η_3	η_4	η_5
σ	0.533	0.0059	1					
η_1	0.0917	0.056	-0.014	1				
η_2	0.3165	0.0787	-0.0058	-0.174	1			
η_3	-107.81	38.65	-0.092	0.12	-0.0346	1		
η_4	-0.034	0.0107	0.0081	0.1288	-0.76	-0.235	1	
η_5	0.352	0.0683	0.0069	-0.83	-0.03	-0.123	-0.16	1

In this regard fragility is defined:

$$F(Sa_i) = P(C - D \le 0 \mid Sa_i), \tag{12}$$

Where $\Pr\lfloor E \vert \mathrm{S}_{\mathrm{a_i}} \rfloor$ denotes the conditional probability of event E given variables $\mathrm{S}_{\mathrm{a_i}}$, i.e., spectral values at the first impulsive mode. Different estimates of fragility can be obtained depending on how one treats the epistemic uncertainties; one is to treat the epistemic uncertainties present in $\mathbf{\Theta}$ in the same manner as the aleatory uncertainties in $\mathbf{x}$. One can show (Der Kiureghian 1989 and 1999) that the fragility estimate then is simply the mean of the fragility function with respect to the distribution of $\mathbf{\Theta}$, i.e.,

$$\widetilde{F}(Sa_i) = \int_{g(\mathbf{x},\,\varepsilon;\ \widetilde{\mathbf{\Theta}};\ Sa_i)\le 0} f(\mathbf{x})\ \varphi(\varepsilon)\ f(\mathbf{\Theta})\ d\mathbf{x}\ d\varepsilon\ d\mathbf{\Theta}, \tag{13}$$

Several methods like FORM (First Order Reliability Method) and SORM (Second Order Reliability Method) and simulation techniques (Melchers 2002) are available to estimate integrals in Eqs. 13. Among these methods Monte Carlo simulation and CaLREL (Liu et al 1989) software were used to develop fragility curves in this study.

Validity

ALA (2001a and b) developed a database of the seismic performance of on-grade cylindrical steel storage tanks based on information in the technical literature. The database inventory consists of a mix of welded, riveted and bolted tanks for water and petroleum product storage. ALA ranked damage states according to increased repair costs for a tank. For instance, DS=2 is for roof damage and pipe damage, generally 1% to 20% loss ratios; DS=3 is for elephant foot buckling with no leaks, generally 40 % to 100% loss ratio; and DS=5 is for complete collapse, generally 100% loss ratio. ALA also described the type of damage observed after earthquake. In this paper analytical data and the Bayesian approach were used to determine tank specific fragilities and also critical failure mode fragilities. ALA database was selected as the real world data and among the 532 tanks in this database 21 tanks were selected for further study. As an example, the seismic fragility of a steel tank having the specifications shown in Table 3 (ALA 2001) is evaluated.

Table 3. OV hospital tank specification. San Fernando earthquake 1971, M=6.7

Tank ID	PGA	D(m)	Ht(m)	liquid height(m)	Pct Full	Damage Observed	Remark	Anchorage
OV Hospital	0.6	17	12	10.8	0.9	Elephant foot buckle, 3m long floor/shell tear; inlet outlet piping damage; loss of content. Roof rafter buckled	Welded steel tank	Un-anchored

In developing the seismic demand model for EFB failure mode in Eq. 6 and welding failure at the junction between bottom plate and shell (BPR) in Eq. 9, it is assumed that t_s and t_b are random variables with 0.004 and 0.002 standard deviations respectively. This assumption was made to model the corrosion effect on the tank shell and bottom plate thicknesses. Developed predictive fragilities are shown in Fig. 4. EFB fragility and BPR fragility are combined with an "or gate" as shown in Eq. 14.

$$P_{f\ event\ above\ or\ gate} = 1 - \prod_{i=1}^{n} [1 - P_{f_i}]_{component\ below\ or\ gate} \tag{14}$$

In which P_f shows the probability of failure for combined failure modes, P_{f_i} is probability of failure for each failure modes, and $i = 1,...,n$ is the number of failure modes. Spectral acceleration at impulsive mode was assumed 2.5 times of PGA value. It is observed that the probability of failure at S_{a_i} =1.5g for EFB, BPR, and combined EFB/BPR are 55%, 95%, and 98% respectively which is considered as a good agreement with real data. Table 4 shows the results for 21 tanks. Among these results, 15 tanks are in good agreement with real world data, 5 tanks are in moderate agreement, and 1 in weak agreement, which shows that the developed models are valid.

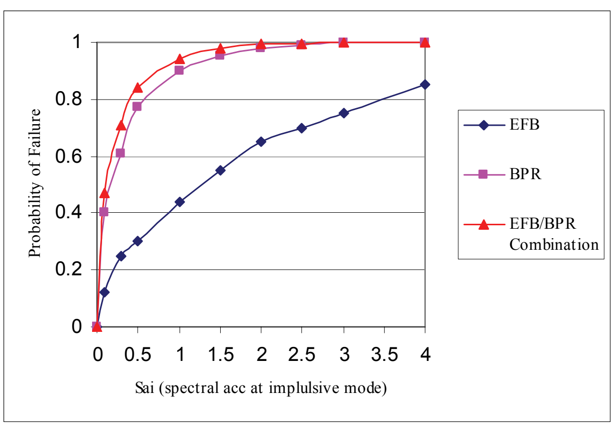

Fig. 4. Predictive fragilities for OV hospital tank

Table 4. Comparison of developed models results and real world data from ALA database

Earthquake	Tank ID	PGA (g)	Equivalent Sa at first impulsive mode	Damage Observed ALA description	DS (Damage State) ALA	Damage Considered BPR = Failure at shell/bottom plate connection, EFB = Elephant Foot Buckling		EFB Probability of Failure if applicable	BPR Probability of Failure if applicable	EFB/BPR Probability of Failure com-bination (or gate) if applicable	Conclusion closeness to reality
						EFB	BPR				
Long Beach 1933 M6.4	A	0.17	0.425	Failed, also oil splashed from top	4	yes	yes	0.1	0.3	0.4	moderate
Long Beach 1933 M6.4	C	0.17	0.425	Damage to upper shell course but no elephant foot buckle. Portions of shell 200 failure	4	no	no	0.03			good
Alaska 1964 M8.4	C, Shell oil at anchorage area	0.2	0.5	Damage to roof, top wall, roof rafters, bottom wall buckled EFB	4	yes	no	0.17			moderate
Alaska 1964 M8.4	J	0.2	0.5	Extensive bottom shell buckling, loss of contents	4	yes	no	0.2			moderate
Alaska 1964 M8.4	AA7	0.2	0.5	Severe elephant foot buckling	4	yes	no	0.253			moderate
San Fernando 1971 M6.7	OV Hospital	0.6	1.5	Elephant foot buckle, 3 m long floor / shell tear; inlet outlet piping damage; loss of contents. Roof rafters buckled	4	yes	yes	0.55	0.95	0.9775	good
Imperial Valley 1979 M6.5	IID El Centro	0.49	1.225	Roof damage and spill due to sloshing. Tank may have uplifted	2	no	no	0.08			good
Imperial Valley 1979 M6.5	IP 13	0.24	0.6	Elephant foot buckling 6 to 8 inches outwards over 90 degree arc, shell / bottom separation, relief piping damaged, cracks in epoxy coating on floor, gauge-anti-rotation pipe broke from floor, floating roof level indicator cable broke	4	yes	yes	0.672	0.94	0.98	good
Coalinga 1983 M6.7	Site C Tank 7	0.39	0.975	Roof seal damage, oil Built to API 650 splashed over top. Tank pounded into foundation 4 inches, uplifted and with steel tear and significant leak of contents where pipe entered through bottom plate. Pipe support moved 4 inches	4	no	yes		0.49		good
Loma Prieta 1989 M7	Lube 60 of 60	0.13	0.325	Elephant Foot Buckling . Walkway between this tank and another pulled loose and fell to ground	3	yes	no	2.00E-04			weak
Loma Prieta 1989 M7	San Jose 1 of 32	0.17	0.425	Severe bending and buckling of internal pan	2	no	no	1.00E-03			good
Loma Prieta 1989 M7	San Jose 2 of 32	0.17	0.425	Severe bending and buckling of internal pan	2	no	no	1.00E-04			good
Loma Prieta 1989 M7	131 PG&E Moss Landing 1	0.24	0.6	Failed at floor/shell connection. Junction possibly corroded. Tank drained rapidly. Top shell course buckled	4	no	yes		0.8		good
Costa Rica 1992 M7.5	12	0.35	0.875	Elephant Foot Buckling	4	yes	no	0.28			moderate
Lander 1992 M7.3	BDVWA A	0.56	1.4	EFB around entire tank, failed at shell / bottom plate at 2 locations.6” overflow pipe failed, lifted 2 feet out of ground. Tank shifted 3” laterally. Failure of side pipe	4	yes	yes	0.4	0.8	0.88	good
Lander 1992 M7.3	CSA 70-1	0.47	1.175	EFBall around, shell tearing, pullout of dresser coupling for 2 side attached pipe	4	yes	yes	0.18	0.8	0.836	good
Northridge 1994 M6.7	Santa Clarita	0.56	1.4	EFB, roof damage	4	yes	no	0.85			good
Northridge 1994 M6.7	Valencia Round Mountain	0.56	1.4	No tank damage	1	no	no	1.00E-10			good
Northridge 1994 M6.7	Hasley	0.5	1.25	No tank damage	1	no	no	1.00E-03			good
Northridge 1994 M6.7	4 Million	0.55	1.375	No damage	1	no	no	1.00E-10			good
Northridge 1994 M6.7	Newhall 5	0.63	1.575	Roof rafter damage, EFB, inlet/outlet piping sheared	4	yes	no	0.4			good

Conclusion

The methodology developed in this paper for assessing seismic demand of critical failure modes of un-anchored on-grade steel storage tanks is unique in the sense that it is based on analytical data, and properly incorporates the mechanical and physical specification of tanks in assessing seismic fragilities. Although the methodology presented in this paper is aimed at developing a probabilistic seismic demand model for critical failure modes of tanks, the approach is quite general and can be applied to other systems and equipments in petroleum complexes.

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